Quantum State Spectroscopy of Atom-Cavity Systems

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Macroscopically distinct superpositions of states, also known as Schrödinger cat states, and the existence of entanglement between multiple systems, are the defining features of quantum physics. As technology has moved forward, such quantum correlations have become central to the design and manufacture of quantum technologies, including quantum information systems, quantum computing, and metrology. As systems grow in complexity, understanding the quantum correlations becomes highly challenging. Quantitative measures can be used to understand very specific properties from expectation values of observables and entanglement entropies, to deeper system correlations. Graphical representations of a system's density matrix can also be used to gain insight into correlations within a system. However, as a system grows in size or complexity, this rapidly becomes too difficult to interpret, let alone display. Phase space methods, providing similar utility to the probability density functions of classical physics, are an alternative approach to gaining an intuitive understanding of a system's state. In particular, Wigner functions are frequently used to visualise quantum states because they clearly display the quantum correlations associated with macroscopically distinct superpositions of states (such as those found in Schrödinger cat states). Here, the presence of interference terms in the form of oscillations, that take on both positive and negative values, allow us to see these quantum correlations.

In recent work we have shown how a complete and continuous Wigner function may be constructed for any system and have used it to generate informationally rich visualisations of qubit-cat states, as well as atomic states, allowing us to determine key state characteristics by inspection alone [1–4]. In this work [5] we explore the possibility of an analogous process to quantum state tomography that uses our phase-space representation. Specifically, we seek to visualise in an accessible way as much of the full Wigner function of a quantum system as is possible. That is, we propose a form of quantum state spectroscopy. The images that this method produces are analogous to the usual time-frequency spectrograms, but over the full paramterisation of the phase space of the quantum state. These spectrograms allow us to reconstruct important elements of the state, verifying certain quantum properties. We note that experimental realisation would rely on the ability to measure the correct physical quantities, which take the form of displaced parity operators, for each component of the overall system being studied.

Using this approach, we consider how best to graphically represent one of the most important processes in quantum physics – the interaction of light and matter. Here we consider example quantum state spectrograms for the simplest fully quantum mechanical model of a two-level atom (qubit) coupled to a single quantum field mode (the Jaynes-Cummings model), and some of its simple extensions. We show how different quantum states, such as a separable state of a qubit coupled to a Schrödinger cat state and an entangled qubit-field cat, can be clearly identified using this approach. Furthermore, we show how our visualisation scheme enables us to obtain substantial information and greater insight into the state of quantum systems; including non-classical correlations such as cat swapping/sharing. Extensions to larger systems will undoubtedly shed further insight into the nature of quantum correlations in present and future quantum technologies.

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